

# Interferometric detection of gravitational waves: how can a wild roam through mindless mathematical laws really be a trek towards the goal of unification?

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## Abstract

The event GW150914 was the first historical detection of gravitational waves (GWs). The emergence of this ground-breaking discovery came not only from incredibly innovative experimental work, but also from a centennial of theoretical analyses. Many such analyses were performed by pioneering scientists who had wandered through a wild territory of mathematical laws. We explore such wandering and explain how it may impact the grand goal of unification in physics.

In November of 1915 Albert Einstein sent his historical paper on the general theory of relativity [1] to the Prussian Academy of Science. Two subsequent papers by the same Einstein, in 1916 [2] and in 1918 [3], predict that any massive object moving through space-time will generate GWs. Thereafter, in September of 2015 the Laser Interferometer Gravitational-Wave Observatory (LIGO) detected the first GW signal from a binary black hole merger; this remarkable,

historical event is known as GW150914 [4] and is in alignment with the goal of establishing a unified field theory of physics. The event GW150914 represented a cornerstone for science and for gravitational physics in particular. In fact, this remarkable event equipped scientists with the means to give definitive proof of the existence of GWs, the existence of black holes having mass greater than 25 solar masses, and the existence of binary systems of black holes which coalesce in a time less than the age of the universe [4]. The one century period between these two historical events encompasses a great interplay of experimental and theoretical advancements. Who on Earth would have guessed that pioneering scientists, who have wandered through a wild territory of mindless mathematical laws, would ultimately help pave-the-way to the creation of LIGO and the detection of GW150914?

In order to take science to the next level, we must first establish and experimentally-verify a unified field theory of physics so it can be further applied to disciplines such as chemistry, biology, engineering, computing, and medicine, etc. Thus, in order to develop and assess candidates for such a grand unified theory, we must be able to probe systems of massive objects throughout the universe. To learn how such systems operate and interact, we must be able to detect and analyze the GWs that they generate in the first place; this motivates the hunt for GWs. Detecting GWs is a mighty challenge because it requires highly-sophisticated technology that is capable of making extremely precise measurements. Consequently, in order to advance science and establish a unified field theory, scientists working in this field need such tools to detect and analyze GWs. Therefore, the creation of LIGO and the GW150914 detection are colossal, powerful steps forward in the trek that aims to achieve unification. A great hope is indeed the future detection of primordial GWs, which could show that gravity might also be brought into the unification and will be, in turn, a next great step toward establishing the root of a unified field theory that may be verified in the laboratory [5].

Before we explore aspects of the mindless wandering which ultimately led to the ground-breaking detection of GW150914 by LIGO, let us briefly touch on some pertinent background material: what is a GW and which types of astrophysical objects generate GWs that scientists can detect? Let us consider an analogy. Suppose that you're standing along the shore of a vast lake that is flat calm. If you reach down and move your hand through the water, then your action will cause a disturbance, or ripple effect, as the generated water waves ensue the trajectory of your hand and propagate outward in the lake. Albert Einstein's general theory of relativity predicts a similar effect: if an object with mass is moving through space-time, then this action will cause a disturbance as the generated GWs ensue the trajectory of the object and propagate outward in the universe. Thus, according to the general theory of relativity, any accelerating object with mass should generate GWs. But small ripples in space-time would dissipate relatively quickly, just as small ripples in the lake would fade out before they could be seen by a second observer standing along the shore at a sufficiently far distance. Therefore, in order to detect GWs on Earth that are generated from distant sources throughout the universe, scientists search

for enormously massive objects, such as neutron stars or black holes, that are capable of generating GWs that propagate all the way to Earth.

In 1974 Russel A. Hulse and Joseph H. Taylor discovered the Hulse-Taylor binary (or PSR 1913+16) using the Arecibo radio telescope [6]. The Hulse-Taylor binary is a compact star system consisting of two neutron stars (one of which is a pulsar - i.e. a neutron star emitting electromagnetic radiation) that orbit around a common center of mass. The Hulse-Taylor binary was the first binary star system to be observed and is regarded as the first indirect proof of the existence of GWs as predicted by the general theory of relativity. Even though the first efforts at direct GW detection started long before the Hulse-Taylor binary (see the recent paper by the Nobel Laureate G. F. Smoot and collaborators on the history of GW research [7]), this astronomical revelation generated intense excitement in the physics community while further motivating efforts to create new technology for direct GW detection. In fact, this historical finding was so significant that it earned Hulse and Taylor the 1993 Nobel Prize in Physics [8].

On one hand, the event GW150914 and the subsequent event GW151226, which is the second direct detection of GWs from a 22 solar-mass binary black hole coalescence [9] are considered to be one of the greatest triumphs of experimental physics because they represent the most precise experimental measurements in the whole history of science. In fact, they involve measuring distances on the order of  $10^{-18}$  meters. This is a distance shorter than the proton's radius! In a recent interview during a trip in Italy, the famous theoretical physicist Kip Thorne, who is one of the LIGO's Founding Fathers and is, in turn, a candidate for the Nobel Prize in Physics for the direct detection of GWs, claimed, with a very remarkable modesty that [10] (translated from the Italian language) "*The next Nobel Prize for Physics? It must be assigned to the gravitational waves, but I do not deserve it. The real heroes of this event (the detection of gravitational waves) are the experimental physicists who resolved all the practical problems of a very complex experiment making possible this discovery. I am not among them.*".

On the other hand, the goal of this Essay is to stress that the event GW150914 and the subsequent event GW151226 arise not only from extremely precise experimental work, as it has been emphasized by Thorne, but also from a centennial of theoretical analyses which have been performed through lots of mindless mathematical laws.

Einstein predicted the existence of GWs in his theoretical, historical paper [2] and improved his analysis two years later [3], claiming that this second paper permitted him to correct a trivial mistake in his previous work [2]. In any case, Einstein's position on the existence or non-existence of GWs changed various times. In 1936 Einstein wrote to Max Born [11]: "*Together with a young collaborator (Nathan Rosen), I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation. This shows that the non-linear general relativistic field equations can tell us more or, rather, limit us more than we have believed up to now*". Einstein submitted this research titled "*Do Gravitational Waves Exist?*" to the Physical

Review with Rosen as the co-author [12]. Although the original version of this manuscript no longer exists, one can infer from the letter of Einstein to Born [11, 12] that Einstein and Rosen answered "No" in response to the question of the title. Despite Einstein's great eminence and fame, the Physical Review returned the paper to Einstein with a critical review and the kind request that the journal's Editor, who was the physicist John Torrence Tate Sr., "*would be glad to have [Einstein's] reaction to the various comments and criticisms the referee has made*" [12]. When Einstein received the returned paper with the critical review he became infuriated and decided to ultimately withdraw the paper from the Physical Review with a very irritated letter (Einstein was so furious that he wrote the letter in Germany instead of in English!). Details of this curious story can be found in [12]. In any case, Einstein, who decided to publish the paper with the Journal of the Franklin Institute in Philadelphia [13], again reversed his opinion on the existence of GWs in 1937. In fact, Einstein's new collaborator, Infeld, discovered a mistake in the paper of Einstein and Rosen during a discussion with the relativist Howard Percy Robertson [12, 14], who is famous for his works in cosmology (he was co-author of the widely known Robertson-Walker metric). Infeld reported his discussion with Robertson to Einstein. This time Einstein not only agreed with the arguments of Infeld and Robertson, but also added that he had coincidentally and independently found another mistake in the paper that he wrote together with Rosen [12, 14]. At that time the paper was in the phase of proofs for the Journal of the Franklin Institute. Thus, despite that the journal had already accepted the paper in its original form, Einstein was forced to explain that fundamental changes in the paper were required because the consequences of the equations derived in the manuscript were incorrect [12]. Then, the paper of Einstein and Rosen was published with radically altered conclusions [13]. Differently from Einstein, Rosen did not change his opinion on the non-existence of GWs [12]. In fact, he was not happy with the paper [13] and published a paper in a Soviet journal by claiming the non-existence of GWs [15]. In the following year, Einstein reversed his opinion one more time. In fact, in 1938 Einstein wrote a paper together with Infeld and the mathematician and physicist Banesh Hoffmann [16]. This was a (fruitless) attempt to find a theory which could unify gravity and electromagnetism, where one of the assumptions of the paper was that GWs should not exist [16]. Thus, in general, Einstein's attitude on the existence or non-existence of GWs was of substantial uncertainty. This was stressed by the same Einstein in a lecture that he delivered to the University of Princeton exactly one day after he corrected his paper [13]. In fact, he concluded the lecture by saying "*If you ask me whether there are gravitational waves or not, I must answer that I do not know. But it is a highly interesting problem*" [12, 14].

A key event in GW research occurred in the 1950s, when the famous astrophysicist Hermann Bondi, with his collaborators Felix Arnold Edward Pirani and Ivor Robinson, published the fundamental paper [17]. In that work, they showed that Rosen's arguments in [15], which claimed that GWs do not exist, were incorrect. Furthermore, they also correctly predicted the effect that would eventually be used in the future by LIGO to detect the real GWs of GW150914

and GW151226. The most remarkable contribution on this issue was by Pirani, who also wrote the important papers [18 - 20].

Thus, for the theme of this Essay, we note that for more than 40 years - i.e. from Einstein's prevision in [2,3] to the work of Pirani and Bondi [17 - 20] - the primary goal of GW detection was not yet well-defined. Instead, we've had a gigantic and intriguing, but also wild and controversial, debate regarding the existence or non-existence of GWs through a hefty amount of theoretical work over a vast territory of mindless mathematical laws. In this case, identifying the real goal to be approached (the detection of GWs) was a greatly disputed issue. In order to ultimately realize the significance of GW detection and develop the mathematical formalism to describe the GW phenomena, numerous pioneering scientists invested an enormous amount of time and energy to wander through this mindless territory by asking questions, considering hypotheses and conducting thought experiments. We indeed cited only the most important contributions to the debate on GWs, which also involved the work of Eddington [21], Beck [22], Baldwin and Jeffery [23]. Despite Einstein's claim that, even admitting the concrete existence of GWs, their detection will always be impossible because of the very weak coupling between matter and GWs [3], Pirani and collaborators [17 - 20] predicted a GW effect that could be observed. They indeed proposed the geodesic deviation equation as a tool for designing a practical GW detector. In other words, if a GW propagates in a region of space-time where two free-falling test masses are present, the GW effect will drive the masses to oscillate.

Recently, one of us, C. Corda, generalized the work in [17 - 20] to the framework of extended theories of gravity [24 - 26], also together with collaborators [27]. In fact, the motion of the test masses due to a GW in extended theories of gravity is different with respect to the motion of test masses due to a GW in the general theory of relativity [24 - 27]. This is because in the standard general theory of relativity one finds only two different, independent GW polarizations, while in extended theories of gravity the independent GW polarizations are at least three [24 - 27]. The results in [24 - 27] could become very important in the framework of the nascent GW astronomy in order to ultimately discriminate between the general theory of relativity and extended theories of gravity, with important consequences concerning the final unification of theories. An extension of the general theory of relativity could indeed be necessary in order to achieve such a prestigious goal - see [24] for details.

The greatest problem in GW interferometric detectors is that the "signal", which is the motion of the test masses, is very weak. In fact, let us consider a GW which originates from an astrophysical source and propagates in a region of space-time where two test masses stay separated by a distance on the order of a few kilometers. The GW drives such test masses to oscillate with an oscillation amplitude of order of  $10^{-18}$  meters. In order to achieve this extremely difficult measure, GW physicists use the so-called *interferometers*. These are extremely precise "yardsticks" that use the properties of light in order to realize this almost impossible measure. Thus, on one hand, the main task for experimental physicists is to figure out how to reduce the potential noise interference that

makes such tiny measurements so difficult to perform in practice. The most important source of noise for interferometric GW detectors is the seismic noise, but many additional sources of noise are present; see [28] for details. On the other hand, reducing the potential impact of various sources of noise has not been sufficient in order to guarantee the GW detection. We have seen that an enormous amount of computations and mathematical laws were necessary only to identify the goal of GW detection. During the development of interferometric GW detectors, which starts from the original intuitions of the Soviet physicists Mikhail Evgen'evich Gertsenshtein and Vladislav Ivanovich in the early 1960s [29] and continues until the LIGO discovery [4], an immense number of simulations and data analyses have been indeed performed by using various mindless mathematical laws. An important and very useful tool has indeed been numerical relativity, which is the branch of the general theory of relativity that creates algorithms and uses numerical methods to analyze and potentially solve problems. To achieve the detection of the event GW150914, many researchers have worked hard to obtain numerical solutions to the problem of a binary black hole system, which enables them to get increasingly accurate computational results that describe the GWs emitted by such a system [4]. In fact, scientists first generated the wave forms by simulating binary black holes, black hole - neutron stars and neutron star - neutron star mergers by employing numerical relativity and powerful super computers in order to have many template waveforms for checking the possible detections [30 - 32]. Thus, the work of experimental physicists must be complementary to the work of theorists.

Concerning the previously cited possibility of ultimately discriminating between the general theory of relativity and extended theories of gravity, only a perfect knowledge of the motion of the test masses, which are the beam-splitter and the mirrors of the interferometer, will permit one to determine if the general theory of relativity is the definitive theory of gravity. At the present time, the sensitivity of the current ground-based GW interferometers is not high enough to determine the motion of the test masses with an absolute precision. A network including interferometers with different orientations is indeed required and we're hoping that future advancements in ground-based projects and space-based projects will have a sufficiently high sensitivity. Such advancements would enable physicists to determine, with absolute precision, the direction of GW propagation and the motion of the various involved mirrors. In other words, in the nascent GW astronomy we hope not only to obtain new, precise, astrophysical information, but we also hope to be able to obtain a perfect knowledge of the motion of the test masses. Such advances in GW technology would equip us with the means and results to ultimately confirm the general theory of relativity or, alternatively, to ultimately clarify that the general theory of relativity must be extended. This ambitious result, we observe, will only be obtained through a correct mixture of technological innovation, collaboration, debate, and wild roams through mindless mathematical laws with adherence to the scientific method. This achievement will surely be a great step forward in the trek towards the grand unification of physics.

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